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GROUND COLLISION WARNING SYSTEM PERFORMANCE CRITERIA FOR HIGH MANEUVERABILITY AIRCRAFT

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Controlled flight into terrain (CFIT) constitutes a large category of Class A mishaps. CFIT occurs when the pilot's attention is diverted in a controllable aircraft resulting in impact with the ground. Warning systems which provide aural warning of impending CFIT have existed in commercial aircraft for some time. Because tactical aircraft operate at low altitudes and have high performance capabilities, systems for commercial aircraft have not proven suitable for tactical aircraft. Due to differences in missions, sensors, hardware configurations, performance capability, etc., each warning system developed for a tactical aircraft will be unique. This report presents performance criteria for use in developing a ground collision warning system for tactical aircraft.

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PREFACE

This report presents performance criteria for a Ground Collision Warning System (GCWS) for high maneuverability (MIL-STD-1797 class IV) aircraft. A GCWS is a passive warning system which gives aural warning to the pilot of impending Controlled Flight Into Terrain (CFIT). Controlled flight into terrain is defined as collision with the ground in a functionally controllable aircraft. CFIT occurs when the pilot is distracted or disoriented and loses situational awareness.

CFIT constitutes the second largest category of Tactical Air Force class A mishaps. For the period 1980-1985, 47 class A mishaps may have been prevented by a GCWS. Over this period, 17 accident board presidents have recommended GCWS which may have potentially saved 52 lives.

CFIT warning systems have been mandatory on commercial aircraft since 1976 and have greatly reduced the incidence of CFIT mishaps. The Air Force has installed systems on some transport aircraft. However, considering the mission scenarios and performance capabilities of high maneuverability aircraft, these systems have not proven suitable to tactical situations. This created a need to develop improved warning systems for high maneuverability aircraft.

Many terms have been used to describe a CFIT warning system. Some of these terms are: Ground Collision Avoidance System (GCAS), Ground Collision Warning System (GCWS), Low Altitude Warning System (LAWS), and Ground Proximity Warning System (GPWS). GCAS has become the acronym most commonly used to define passive warning systems for high maneuverability aircraft. Unfortunately, "Avoidance System" can give a false impression of the warning systems function. Avoidance implies an active rather than a passive system. A more appropriate name for a passive warning system would be Ground Collision Advisory System. GCWS was chosen for this report since it reflects the actual system function, and in the hope that this term is used in the future to refer to passive systems.

ACKNOWLEDGMENTS

I would like to acknowledge the work of my colleagues. Mr. Wayne Thor, Flight Stability and Control Engineer, who designed the A-10 LAWS algorithm. The development of the LAWS system and the LAWS philosophies provided the basis for this report. Lt. Bob Lombardi, ASD Flight Control Engineer, who assisted in the creation of the performance criteria.

TABLE OF CONTENTS

ILLUSTRATIONS

SECTION I

INTRODUCTION

An ASD A-10 accident study published in 1981 by Major J.A. Stretch of the Crew Performance Branch, USAF School of Aerospace Medicine stated, "The largest sized category of mishap causes was collision with the ground in a functionally controllable aircraft." This study established the need for a GCWS for the A-10 aircraft.

In response to the need for a GCWS system on the A-10, an ASD engineer, Mr. Wayne Thor, initiated and proposed the ASD Low Altitude Warning System (LAWS) algorithm in 1983. Since June 1984, several development contracts were awarded to Fairchild Republic Corporation to simulate, flight test, and modify the LAWS algorithm. The final contract was completed in February 1988. The LAWS algorithm will be implemented on the A-10 fleet under the Low Altitude Safety and Targeting Enhancement modification.

Ground Collision Warning System developments have been undertaken for high maneuverability aircraft other than the A-10. Due to the state-of-the-art and lack of clearly defined performance criteria, these programs have taken a variety of directions. Parallel development processes have occurred. For a GCWS development to benefit from the lessons learned of its forerunners, a clearly defined set of performance criteria was necessary.

The criteria presented here are based upon the data resulting from simulation and flight testing of the LAWS algorithm on the A-10 (Ref. 2, 4, 5) and also data collected during a simulation evaluation of several warning system algorithms applied to an F-16 aircraft. These criteria are based primarily on pilot comments describing acceptable levels of nuisance warnings and acceptable recovery altitudes. Although developed primarily from an A-10 data base, these criteria are based on human factors considerations which are applicable to all high maneuverability aircraft and may be applied to some military transport aircraft.

The criteria presented are of a statistical nature. The statistical basis for the criteria band is a total of 1,600 simulation and flight test warnings studied during the LAWS development. The percentages of "good", "early", "late", and "crash" were derived from 428 flight test warnings collected during the last flight test in the LAWS development as were the terrain slope data. All valid data points were presented. No data points were declared invalid due to pilot recovery technique or terrain slopes. Data points which were declared invalid were due to radar altimeter anomalies or occurred while the pilot was setting up for another maneuver. This final flight test was conducted with false ground planes which ranged from 0 to 1,000 feet.

The body of the report contains performance criteria which can be lifted out of the report. The remainder of the report contains lessons learned and guidance material.

SECTION II

GROUND COLLISION WARNING SYSTEM (GCWS) PERFORMANCE CRITERIA FOR HIGH MANEUVERABILITY AIRCRAFT

2.1 SCOPE

This document defines the minimum performance requirements of a GCWS for high maneuverability aircraft. The GCWS is assumed to use a downward looking radar altimeter as its primary sensor. This is written as guidance material which can be tailored to the specific needs of the respective aircraft. These criteria are compiled from a limited data base of Low Altitude Warning System (LAWS) flight testing and simulation.

The criteria stated here are a result of pilot comments describing acceptable recovery altitudes and defining at what altitude a recovery is considered to be "early," "good," or "late." The criteria band which defines a "good" recovery altitude was corroborated by over 1,600 simulation and flight test warnings studied during the LAWS development. The percentages of "good," "early," "late," and "crash" were derived from 428 flight test warnings collected during the last flight test in the LAWS development as were the terrain slope data. All valid data points were counted. No data points were declared invalid due to pilot recovery technique or terrain slopes. Data points which were declared invalid were due to radar altimeter anomalies or occurred while the pilot was setting up for another maneuver. This final flight test was conducted with false ground planes which ranged from 0 to 1,000 feet.

The ability of a warning system to meet the criteria presented here is dependent on pilot performance and terrain variation. For this reason, the criteria presented here are of a statistical nature.

2.1.1 PHILOSOPHY

The GCWS is an emergency warning system designed such that the pilot must react appropriately and immediately to avoid impact with the ground. Due to sensor limitations and variation in pilot recovery technique, current state-of-the-art GCWS cannot give adequate warning in all situations while achieving a minimum of nuisance warnings. If autorecovery in conjunction with global positioning system and a digital terrain data base were used, it may be possible to overcome these limitations.

Due to sensor limitations, the pilots will be directed not to rely on the GCWS system for avoiding terrain. The design philosophy is that if a pilot does not commit a ground clearance error, he should never receive a GCWS warning, and if he receives a GCWS warning, he may be assured that he has committed a ground clearance error. This philosophy leaves responsibility and control in the pilot's hands while minimizing nuisance warnings and allowing a level of Controlled Flight Into Terrain (CFIT) protection which would otherwise not occur.

2.1.2 DEFINITIONS

Above Ground Level (AGL) The distance from the altitude sensor on the aircraft to the ground directly beneath it.

Average Terrain Slope The angle of a straight line starting at the valley and ending at the peak of a slope. Also referred to as Terrain Angle.

Bunt Maneuvers Maneuvers with a g between -0.5 and 0.5, bank angle less than 30 degrees, and sink rate less than 144 ft/sec.

Early Warning Any warning issued to the pilot which results in a recovery which is above the MAXA and below the limit altitude.

Emergency recovery procedure Pilot reacts up to but within 1 second after the initiation of audible sound in the pilot's headset using a large percentage of the maximum control authority available to him.

Flight Test Maneuver Descending Constant attitude turn.

Good Warning Any warning issued to the pilot which results in the aircraft's recovery altitude being within the allowable recovery altitude limits.

Late Warning Any warning issued to the pilot which does not permit sufficient altitude for avoiding penetration of the minimum allowable recovery altitude when the emergency recovery procedure is executed or failure to provide a warning, causing penetration of the minimum allowable recovery altitude.

Limit altitude The highest recovery altitude at which a recovery shall occur as shown in Figure 1.

Maneuver Type I (Accelerated Dive) Any maneuver where the aircraft is at greater than 55 degrees of bank and has greater than 16 ftpsps acceleration towards the ground. Defined at the time of the leading edge of the warning signal.

Maneuver Type II (Banked Turns) Any maneuver where the aircraft is at greater than 55 degrees of bank and less than 16 ftpsps acceleration towards the ground. Defined at the time of the leading edge of the warning signal.

Maneuver type III Any maneuver in which the aircraft's angle of bank is less then 55 degrees. Defined at the time of the leading edge of the warning signal.

Maximum Altitude (MAXA) The highest desirable recovery altitude (AGL) (see Figure 1).

Minimum Altitude (MINA) The lowest desirable recovery altitude (AGL) (see Figure 1).

Minimum Design Altitude Warning (MDA) The minimum altitude above the terrain for which the system is designed to issue a warning. Can never be classified as a nuisance or early warning for the purposes of the criteria band.

Nuisance Warning Any warning which the pilot states is unacceptable.

Pilot Reaction Time The time from the initiation of audible sound to the pilot's headset to the time at which the pilot makes a control input which uses at least 25% of the control force available to him.

Pop-Up-Maneuvers 3 to 4 G pull up from low altitude to acquire the target. Followed by a 135 degree bank angle change and 3 G pull to a 45 degree heading change to acquire the target. Should be performed over flat terrain and up and down ridge lines.

Recovery Altitude The first altitude (AGL) at which the ground closure rate becomes zero following a warning. Unless the pilot continues the recovery maneuver and a second minimum occurs due to terrain rise.

Slice Backs A 180-to 220-degree heading change using 120 to 150 degrees of bank and up to 5.0 g (3000 ft to 10,000 ft maximum altitude).

ZSU Breaks A 135 degree descending heading change using 90 to 120 degrees of bank and 3-5 g and unload roll-out-1 g (500 to 200 feet maximum altitude).

2.2 APPLICABLE DOCUMENTS

TAF SON 311-82 Ground Proximity Warning System 27 December 1982

2.3 PERFORMANCE REQUIREMENTS

This section specifies minimum performance requirements for a GCWS used in high maneuverability aircraft.

2.3.1 Minimum Acceptable Level of Performance

The GCWS warning distribution required for the test profiles stated in 2.4.1, 2.4.2, and for simulation demonstrations of rising terrain protection for a statistically significant number of data points is as follows: (Note - round off results in a total of 101%).

	EARLY maximum %	GOOD minimum%	LATE maximum%	CRASH maximum%
Maneuver Type I	12%	76%	12%	1%
Maneuver Type II	20%	60%	20%	1%
Maneuver Type III	10%	80%	10%	1%

No recoveries shall occur above the limit altitude. All flight test data points shall be considered valid unless the pilot takes no recovery action resulting in a late or crash result.

The bands for "good", "early", and "late" warnings are as shown in Figure 1. The X-axis is Sink Rate in feet-per-second (ft/sec) at the time of the warning, and the Y-axis is Recovery Altitude in feet (ft).

The warnings must be distributed such that at least the following percentages fall in each terrain slope category (the warnings shall occur over both rising and falling terrain):

	ABSOLUTE VALUE OF TERRAIN SLOPE RANGE IN DEGREES		
	GREATER THAN ONE AND LESS THAN OR EQUAL TO THREE DEGREES	GREATER THAN THREE AND LESS THAN OR EQUAL TO SEVEN DEGREES	GREATER THAN SEVEN DEGREES AND LESS THAN FOURTEEN DEGREES
MANEUVER TYPE I	30.6%	17.2%	6.7%
MANEUVER TYPE II	17.9%	10.3%	23.1%
MANEUVER TYPE III	9.0%	12.4%	21.7%

Note: These percentages are required for flight test in order to demonstrate the lack of "early" and nuisance warnings and proper terrain filtering methods. Simulation, not flight test is intended to show protection against rising terrain.

GCWS RECOVERY CRITERIA

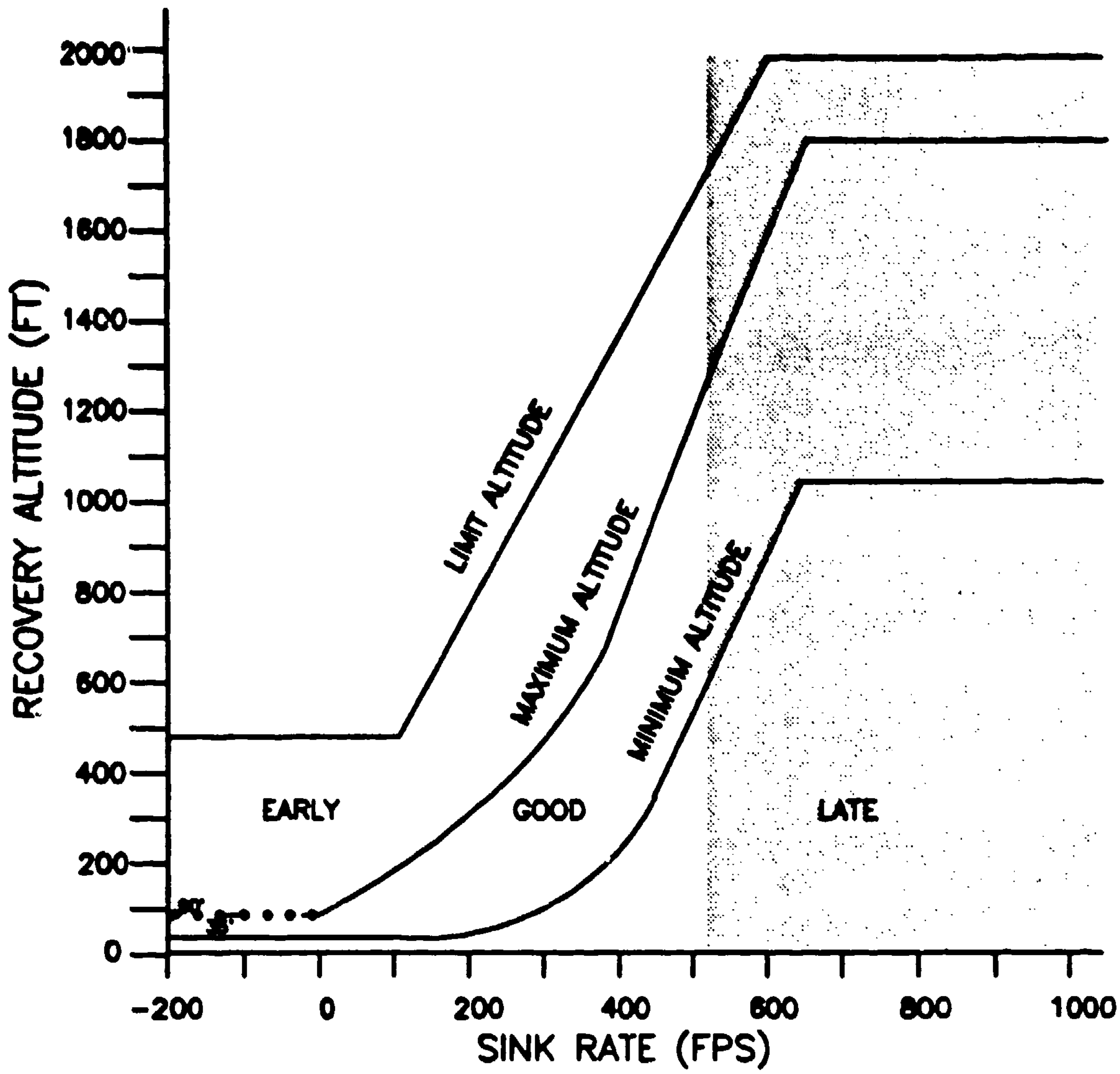


Figure 1

IF 0 FT/SEC < SINK RATE < 650 FT/SEC
MAXIMUM ALTITUDE = $(35 - .0026\ X^3)$ FT
MINIMUM ALTITUDE = $(.2067\ X^2 + 6.93\ X + 90)$ FT

IF SINK RATE < 0 FT/SEC
MAXIMUM ALTITUDE = 90 FT
MINIMUM ALTITUDE = 35 FT

IF SINK RATE > 650 FT/SEC
MAXIMUM ALTITUDE = 1800 FT
MINIMUM ALTITUDE = 1040 FT

SINK RATE = (591.5 SIN X) FT/SEC

FLIGHT TEST DATA IS NOT AVAILABLE FOR THIS PORTION OF THE GRAPH (SEE CRITERIA DISCUSSION).

THIS WILL CHANGE TO REFLECT SYSTEM MINIMUM DESIGN ALTITUDE.

2.3.2 PILOT VEHICLE INTERFACE

2.3.2.0 Pilot Workload

The system shall be sufficiently automated such that the pilot's workload during the mission is not increased for the system to function properly. No additional in-flight tasks shall be required of the pilot to receive a valid warning.

2.3.2.1 Visual displays

The system shall provide an in-op light that is illuminated when the system has failed. The system shall not illuminate the in-op light when the aircraft is outside its envelope of altimeter coverage. This in-op light should be placed on the caution panel but shall not keep the master caution light illuminated so as not to be readily distracting to the pilot (Ref. 3).

The system may provide a visual warning such as a break X. This is to be determined (TBD) by the individual Systems Program Office. While a visual warning may be desirable, it shall not occur prior to the aural warning (see lessons learned).

2.3.2.2 Aural Warning

The GCWS shall provide a single aural warning of "pull up pull up." The warning shall take precedence over all other aural messages.

2.3.2.3 Pilot Selectable Parameters

The system shall not interfere with the settable Low Altitude Warning built into the altimeter system. The system may contain an adjustable altitude buffer which may add to the warning altitude. However, it is recommended that this be in addition to the "pull up" call, and use a different aural warning.

2.3.3 ALTIMETER INTERFACE

2.3.3.1 Altimeter Anomalies

Warnings shall not be issued when the radar altimeter is receiving returns from close proximity aircraft or clouds. Warnings shall not occur due to hardware induced radar malfunctions such as altimeter antenna switching.

2.3.3.2 Pitch and Roll Attitude Coverage

The warning system shall provide above ground level altitude information for a minimum pitch attitude coverage of TBD degrees (nose up) to TBD degrees (nose down) at wings level to TBD degrees (nose up) to TBD degrees (nose down) at TBD degrees of bank. The TBDs should be determined from a review of CFIT accident histories for similar aircraft and missions.

2.3.3.3 Maximum Altitude Coverage

The radar altimeter shall provide a radar altitude signal to at least TBD feet AGL. This shall be consistent with the maximum altitudes necessary for dive recovery as shown in the dive recovery charts in the pilots flight manual TO-1.

2.3.3.4 Extended Warning Capability When Outside Radar Altitude Coverage

Warning capability when outside the radar altimeter coverage, or during invalid radar altimeter information, shall be provided for a limited time using alternate altitude information and extrapolation techniques, providing warning capability.

2.3.4 SPECIAL CONSIDERATION MANEUVERS

2.3.4.1 Negative G Maneuvers

The warning system shall not give early warnings during negative G maneuvers (i.e., bunts, pushovers). This requirement does not exclude negative G maneuvers from being included as a part of the performance evaluation of para 2.3.1.

2.3.4.2 Banked Turns

The warning system shall provide warning coverage which satisfies the performance requirements of para 2.3.1 during turns at bank angles between 75 and 110 degrees over steadily rising terrain with slopes as shown in Figure 2. This requirement shall be demonstrated in piloted simulation.

2.3.4.3 Loops

The warning system shall include extended coverage logic which shall provide coverage during loop maneuvers.

2.3.5 MINIMUM DESCENT ALTITUDE WARNING

The warning system shall issue a warning any time the aircraft descends below the Minimum Design Altitude with the landing gear retracted. The Minimum Design Altitude is TBD feet above ground level. (To be determined by Tactical Air Command directive resulting from pilot comment. See 3.7 para 2.)

2.3.6 THRUST AND GROSS WEIGHT

The GCWS shall provide warnings for all operational thrust levels and gross weights. The GCWS shall include adjustments for TBD stores loadings and TBD gross weight ranges (TBD for the specific aircraft).

2.3.7 RISING TERRAIN PROTECTION

The GCWS shall provide warning over sloping terrain. The minimum coverage shall be as described in Figure 2. This coverage shall be demonstrated in simulation and shall meet the required percentages of "early", "good", "late", and "crash" calls as shown in Figure 1 for each maneuver type. The warnings shall be evenly distributed over the terrain slopes for which warning is required.

2.4 TEST

This section specifies the test/simulation scenarios to be used to evaluate the performance of GCWS. Included are test profiles, mission scenarios, and terrain types. These test profiles are given as examples of mission scenarios and are intended to be tailored to specific aircraft and associated missions. Simulation of the mission scenarios is recommended before actual flight test. Safety buffers, i.e., artificial altitude floors simulating the terrain, shall be used as appropriate during warning verification. No altitude buffers shall be used during mission scenarios.

2.4.1 TEST PROFILES

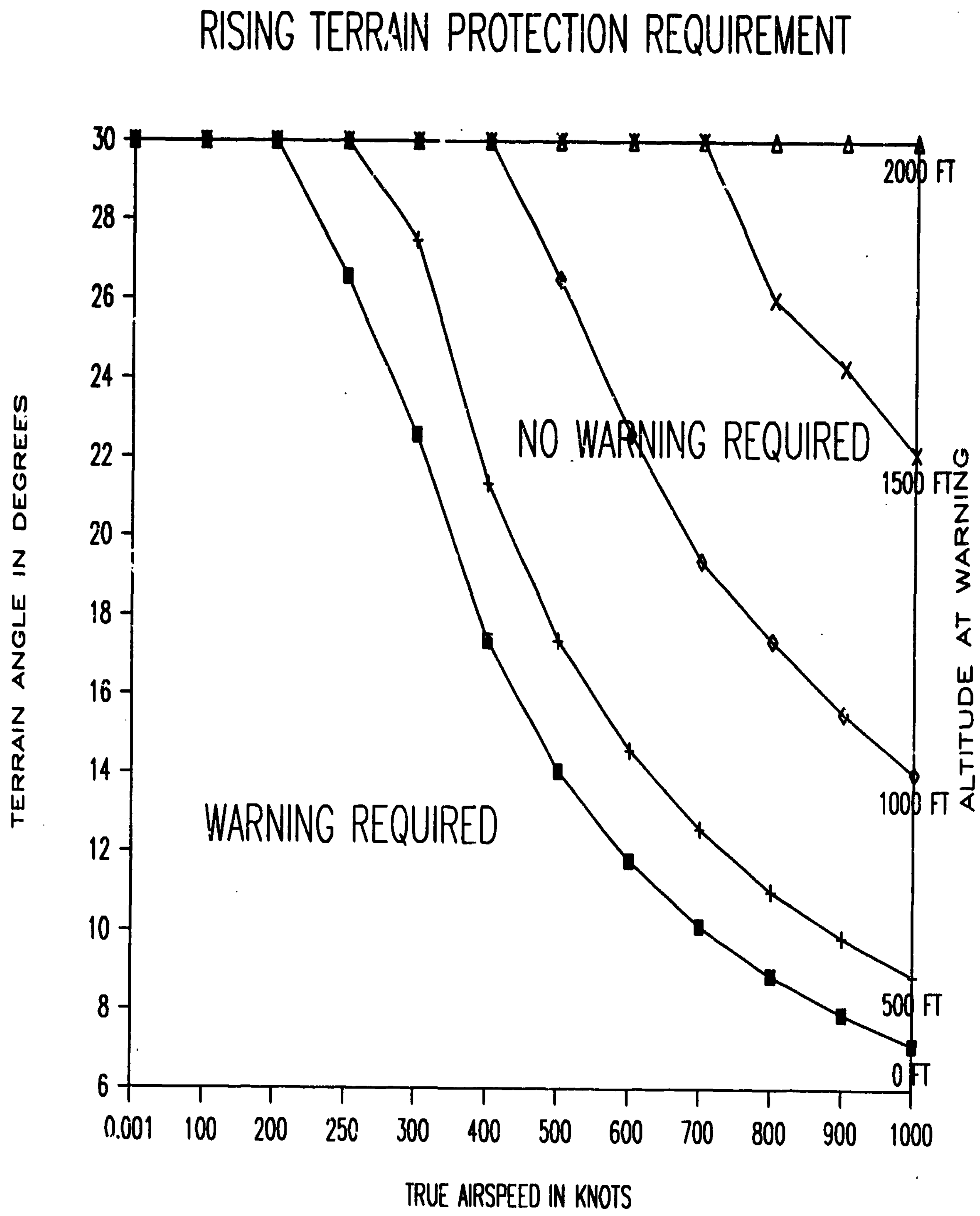
All test profiles shall be flown until a warning occurs or a predetermined safety altitude has been penetrated. When the warning occurs, the pilot shall initiate the emergency recovery procedure.

The operation and flight test maneuvers which must be anticipated and those which evaluation pilots may choose to examine include the following types: pop-ups, slice maneuvers, wings level dives, ZSU break, flight test maneuvers, negative g maneuvers (ie: bunts, pushovers), level flight into rising terrain, banked turns into rising terrain, and dives into rising terrain.

These maneuvers shall be conducted to verify the effects of thrust level, center of gravity, external stores, and gross weight on GCWS performance. Additional or alternate maneuvers may be used with Air Force concurrence.

2.4.2 MISSION SCENARIOS

Flights demonstrating typical air-to-ground operational maneuvers shall be flown with no safety bias to evaluate that nuisance warnings do not compromise system acceptability to the pilot community. These operational maneuvers shall be flown over a variety of terrain types such as flat, rolling, and mountainous. These maneuvers shall be flown under normal operational conditions, no attempt shall be made to fly to warning conditions without an altitude buffer. All warnings generated shall be included in the performance evaluation of 2.3.1. These flights shall be flown by operationally ready pilots rather than test pilots to provide an operational perspective.



RISING TERRAIN PROTECTION REQUIREMENT
TERRAIN ANGLE IN DEGREES
30
28
26
24
22
20
18
16
14
12
10
8
6
0.001
100
200
250
300
400
500
600
700
800
900
1000
TRUE AIRSPEED IN KNOTS
NO WARNING REQUIRED
WARNING REQUIRED
ALTITUDE AT WARNING
2000 FT
1500 FT
1000 FT
500 FT
0 FT

FIGURE 2

SECTION III

LESSONS LEARNED

3.1 INHIBITS

During the simulation and flight test of the LAWS system it was discovered that it was necessary to block the predictive warning under certain conditions when a predictive warning was not necessary. In all cases, a minimum design altitude warning was provided. These modifications were called inhibits. The philosophy used was to eliminate, as much as possible all nuisance warnings while still providing protection against the most common CFIT scenarios. Following is a description of each inhibit and the conditions under which it was used.

3.1.1 Ridge Clip Inhibit

Pilots often fly the aircraft within close altitude of a ridge top under visual flight rule conditions. The pilot observes the ridge top. However, the downward looking altimeter in combination with warning altitude added for rising terrain results in warning conditions being met. Unmodified, this can create an unacceptable level of nuisance warnings. To prevent these ridge clip nuisance warnings in the LAWS system, the warning altitude was reduced to the minimum design altitude warning when the aircraft is in a dive of less than 5 degrees. This 5 degree dive corresponds to a sink rate of approximately 45 feet per second at 300 kts, allowing for up to 2 seconds warning of impending CFIT.

3.1.2 Terrain Slope Inhibit

This inhibit consists of blocking predictive warnings whenever radar altimeter anomalies, stepwise terrain changes, etc. can cause an unrealistic calculation for terrain slope. With a downward looking altimeter system, the higher the terrain slope for which warning protection is given, the more frequent nuisance warnings will become. For the LAWS system, predictive warnings were blocked whenever an excessive terrain slope was calculated. An alternative approach might be to eliminate the altitude added to the warning altitude due to terrain growth prediction when excessive terrain slope is calculated.

3.1.3 Recovery Inhibit

Once the pilot has initiated a recovery, the warning system may calculate an unnecessary warning based on assumed pilot reaction time. This inhibit functioned when a positive vertical acceleration and low ground closure rate were present. These two conditions indicate that the pilot had initiated a recovery. For systems where stick force or position is known, these could be used as a more direct indication of recovery action.

3.1.4 Bunt Inhibit

During the LAWS development, warnings occurred during bunt maneuvers and were perceived by the pilots as being nuisance warnings. These warnings may have been caused by the low pilot reaction time typical for recovery from a bunt maneuver, or by the lag in the filtered vertical acceleration data. The solution used was to block all predictive warnings during bunt conditions (see the bunt maneuver definiton). This inhibit may not be necessary in other systems; however, it is wise to require that nuisance warnings during bunt maneuvers do not occur since these maneuvers would most likely be evaluated last in a warning system development.

3.2 DYNAMIC BIAS

At the initiation of the LAWS development, it was assumed that the recovery altitude should be the same altitude for all flight conditions. Through extensive piloted evaluation, it was determined that a higher recovery altitude is desirable for higher sink rate conditions. This additional altitude is reflected in the recovery band of Figure 1 and has been called "dynamic bias."

3.3 ALTIMETER INTERFACE

The radar altimeter is the weak link in the warning system. This section discusses some of the problems associated with the altimeter interface.

The radar altimeter may not give accurate indication of break lock or break track and may receive returns from other airplanes or clouds creating false altitude readings. False altitude readings can also result from slant ranging during operation on the fringes of altimeter coverage. While these anomalies are benign in altitude displays, they create a serious annoyance when coupled with a warning system. One solution might be to block the warnings following jumps in altitude which are greater than the tracking capability of the radar altimeter.

Due to the limited envelope of sensor coverage, it is useful to "extend" or "extrapolate" altimeter coverage for a limited time with an extended coverage scheme. These schemes correlate the altitude and attitude at the time of break lock to time allowed for extrapolation.

When track is regained following break lock, a large step in altitude reading may occur. This step creates a false calculation of terrain slope. Subtracting the altitude step from the radar altitude before calculating terrain slope prevents a false calculation of terrain rate.

It is necessary to filter the radar altitude due to ground clutter that does not reflect terrain trends. For simulation purposes, this ground clutter can be simulated with 10 ftpsps root mean square white noise.

Studies of the CFIT class A Mishap reports of various fighter aircraft have shown that the majority of CFIT incidents result from maneuvers during which the aircraft attains very high angles of bank (greater than 60 degrees). Therefore, sensor coverage at high angles of bank is important for an effective GCWS for high maneuverability aircraft.

3.4 DEVELOPMENT LESSONS LEARNED

The problem of determining when to issue a Ground Collision Warning is primarily based upon aircraft attitude and performance and as such, is a flight dynamics problem. For this reason the engineering discipline which should have primary input into the development of a GCWS is that of flight dynamics. In the past, other disciplines have been the driving factor in GCWS developments. This has led to nonoptimum design techniques.

Some GCWS algorithms have used "discrete" methods of finding the warning altitude. This can consist of a table lookup or software logic which uses a set of discrete conditions such as airspeeds to switch warning equations or altitudes. Following are some of the pitfalls of using a "discrete" approach:

1. It is difficult if not impossible to test a system which consists of many discrete points.

2. The result could be unpredictable system performance which may be difficult to brief to the pilots.

3. In the past, discrete changes in warning altitude have resulted in excessive nuisance warnings.

4. If algorithm modification is done, it may be difficult to visualize the effect on recovery altitude for all flight conditions.

5. The recovery altitude is a function of dive angle, bank angle, G's, G's available, airspeed, and many other variables. It is difficult, if not impossible, to create a matrix of recovery altitudes versus so many variables.

Therefore, "discrete" approaches to algorithm design are not recommended. An approach that uses point mass equations to represent aircraft response is preferred.

Another development pitfall has been attempts to develop a GCWS through flight test. Extensive piloted simulation is necessary to predict system performance prior to flight test. Simulation is more economical than flight test, allows for the collection of a large statistically significant data base, allows safe realistic low altitude warning generation, can involve a large number of pilots, provides controlled circumstances for maneuvers and terrain slopes, and allows for a readily changeable algorithm. Furthermore, it is normal for the flight test to come last in a development program.

Currently, the most cost and time effective method for GCWS development would be to use the LAWS algorithm and modify it for the aircraft for which a warning system is desired. The modification of the LAWS algorithm to a high speed high maneuverability aircraft simulation was done by a single engineer in less than a day, and resulted in a very effective system. This algorithm incorporates all of the lessons learned and criteria and has been shown to be acceptable to the pilot community. The LAWS algorithm was documented in the NAECON paper "A Low Altitude Warning System for Prevention of Controlled Flight Into Terrain" (Ref. 1).

3.5 DATA REDUCTION

3.5.1 Automatic Determination of Recovery Altitude

The automatic determination of a recovery altitude is a difficult task. The recovery altitude must be evaluated in respect to whether the pilot continued to execute recovery and whether the terrain slope changed drastically after a warning. A group of experts, reviewing a given warning and recovery time history can arrive at several different and justifiable minimum altitudes. This led to many lengthy and heated discussions during the LAWS development regarding methods of determining the minimum altitude. For this reason, the method which was chosen is presented. Following is the six step method of determining the minimum altitude which was used during the LAWS program:

1. The radar altitude rate was examined from the time of the warning until eight seconds after the warning. If two consecutive values were greater than or equal to zero, this was designated as the time of the MIN1 altitude. This will be the first time that the aircraft is no longer closing with the terrain.

2. The radar altitude was examined from the time of the warning until eight seconds after the warning. The minimum altitude over this period was called MIN2 (this altitude could have occurred at the time of the warning as in a Minimum Design Altitude warning, or it could have occurred after the MIN1 altitude as a result of rising terrain, or it could have occurred due to the pilot initiating a pushover after the recovery was completed).

3. If no minimum was determined by step 1 then MIN2 was the minimum altitude.

4. If MIN1 and MIN2 were determined, then critical sink was defined as the minimum vertical velocity at the times of the two minimum altitudes. This was done to determine whether the pilot continued the recovery action and the aircraft attained a lower altitude due to terrain rise or the pilot pitched the aircraft down ending the recovery maneuver.

5. Starting at the earlier of the time at which MIN1 occurred or the time at which MIN2 occurred, search for the lowest radar altitude from that point in time until vertical velocity becomes less than the critical sink rate or until the end of 8 seconds, whichever occurs first. Call this value altitude test.

6. The recovery altitude was determined as the minimum of the altitude test and the altitude at the time of the warning (If the minimum altitude occurred at the time of the warning, the warning was probably a minimum design altitude warning and if so, by definition cannot be evaluated as a "early" warning).

3.5.2 Data Requirements

The following describes the recommended simulation and flight test data requirements. It is necessary to have complete time history and snapshot data for each warning and recovery data point.

<u>SNAPSHOT DATA</u> (digitally tabulated data)

1. Radar altitude at the time of warning (raw and filtered)
2. Barometric altitude at the time of warning
3. Radar altitude rate at the time of warning
4. Vertical acceleration at the time of warning (raw and filtered)
5. Bank angle at the time of warning
6. Dive angle at the time of warning
7. Pitch attitude at the time of warning
8. Ground slope at the time of the warning
9. Aircraft velocity at the time of the warning
10. Inhibit discretes immediately prior to the warning
11. Recovery altitude (Barometric and Radar)
12. Classification of warning by pilot comment and Figure 1 criteria band (i.e. "good", "late", "early", "crash")
13. Date
14. Warning number
15. Pilot identification
16. Recovery load factor and angle of attack- both maximum and average values
17. Pilot reaction time
18. Load factor at the time of the warning
19. Vertical velocity at time of the warning (raw and filtered)

Graphical Data (continuous analog time histories)

The time span shall be from 2 seconds prior to the warning call until 8 seconds after the call.

1. Normal acceleration and maximum g's used during the recovery versus time
2. Altitude versus time (showing both Aircraft altitude and terrain altitude)
3. Dive angle versus time
4. Bank angle versus time
5. Angle of attack and stall angle of attack versus time

SUMMARY DATA

1. Average pilot reaction time for each maneuver type
2. Histogram of pilot reaction time for each maneuver type
3. Recovery altitude versus dive angle for each maneuver type separately and for all maneuvers together (4 graphs total) with probability of "good", "early", "crash", and "late" calls noted.
4. Recovery altitude versus sink rate for each maneuver separately and for all maneuvers (4 graphs total) with the probability of "good", "early", "late", and "crash" calls noted.
5. Pilot questionnaires for each simulation flight (see appendix)

3.6 Visual Warnings

While it may be desirable to include a visual warning, this visual display may be of limited use and could have undesirable effects. Studies of CFIT history have shown that the majority of CFIT cases for high maneuverability aircraft have occurred during maneuvers in which high bank angles (greater than 60 degrees of bank) were attained. During such maneuvers the pilot is generally not viewing the Head Up Display. When the pilot is viewing the Head Up Display, a visual warning may decrease pilot tolerance of nuisance warnings.

With the use of a visual warning, there is the temptation to provide a precursor warning. A precursor warning directly conflicts with the intention of reducing the number of CFIT accidents. Once a precursor warning is available, the pilots may begin to use the warning system as a method to avoid terrain routinely and gain false confidence in the system. This is hazardous in a system which cannot adequately warn in all cases due to sensor limitations and may actually increase the incidence of CFIT. While visual warnings may be desirable, they should never be precursor warnings in systems in which the sole sensor is downward looking.

3.7 CRITERIA DISCUSSION

Fifty-five degrees angle of bank was used as the cutoff for the banked turn maneuver definition for several reasons. Since it is more difficult to provide timely warning for banked maneuvers, and since most CFIT incidents occur during high bank angle maneuvers (greater than 60 degrees of bank), it was important to clearly separate highly banked maneuvers from the less banked maneuvers. Using greater than sixty degrees of bank as the cutoff for banked maneuvers separates the banked turns very distinctly from the more wings level maneuvers, assuring that the algorithm provides adequate warning during banked maneuvers. However, for flight test purposes, a five degree tolerance was necessary. This tolerance was used to avoid the situation of a pilot holding a 2g banked turn at slightly less than 60 degrees angle of bank being classified as a wings level dive when a banked turn classification was desired. Therefore, greater than 55 degrees angle of bank was chosen for the banked turn definition. This definition for banked turns assures that adequate warning is provided for banked maneuvers.

The LAWS system provided a minimum design altitude warning. This consisted of a logic statement which provided a warning whenever the radar altitude was less than 90 feet. The minimum design altitude warning determines the maximum recovery altitude for zero sink rate. The existence of an minimum design altitude warning was a Tactical Air Command directive for the LAWS system and may not necessarily be the same for other systems. If a different minimum design altitude is chosen, the criteria band would need to be adjusted to this altitude.

Eighteen degrees of terrain slope was initally chosen as the maximum terrain slope for which warning would be provided for several reasons. CFIT histories for high maneuverability aircraft show that few CFIT's occur for terrain over 14 degrees slope. It was reported that over 95 percent of the world's terrain has a slope of less than 18 degrees. If warning is provided for high terrain slopes, without a forward looking sensor, an excess of nuisance warnings would be issued.

Without a complete review of the time histories for each warning and recovery data point, the meaning of the summary graph can be unclear. For instance, during the LAWS testing, bunt maneuver recovery altitudes landed inside the criteria band but were judged by the pilots to be nuisance warnings. Although the banked turn summary graph showed a high percentage of "early" warnings, the pilots generally judged these to be acceptable warnings. These "early" warnings during banked turns were primarily ridge clips. The elimination of these "early" warnings would eliminate warning capability for banked turns into rising terrain utilizing a downward looking sensor.

Another shortcoming is that there is very little data to support the criteria band where sink rate is greater than 500 feet per second. Collection of pilot comments and recovery data for future warning system developments on high speed high maneuverability aircraft will increase confidence in the criteria for these sink rates.

SECTION IV

CONCLUSION

The adequacy of a warning system is highly dependent on the pilot's reaction time and magnitude of the pilot's control inputs. During the LAWS flight testing, the pilot was instructed to execute an emergency recovery at warning and pull to the stall warning. This allowed for large variations in recovery technique and gave a spread in recovery altitude which was representative of actual operational recovery techniques. By this method, a realistic spread of recovery altitudes was achieved in contrast to the results from a canned maneuver. This allowed for the algorithm to be designed for a range of pilots. The criteria envelope for a "good" recovery was corroborated by over 1,600 flight test and simulation warnings in conjunction with pilot comments.

Warning system performance is also influenced by changes in terrain slope following the warning. It is difficult, if not impossible, to arrange a flight test so that warnings can be generated over predetermined terrain slopes. For this reason, the number of warnings occurring over each terrain slope was counted and the warnings were categorized to show the percentages of warnings for each terrain slope band. This categorizing of terrain slopes will guarantee a uniform application of the criteria. Flight testing can demonstrate the lack of nuisance warnings over a variety of terrain types but cannot consistently demonstrate rising terrain protection. Demonstration of rising terrain protection must be accomplished in a simulation environment.

The criteria presented are of a statistical nature. The percentages of "good", "early", "late", and "crash" were derived from 428 flight test warnings collected during the last flight test in the LAWS development, as were the terrain slope data. All valid data points were presented. No data points were declared invalid due to pilot recovery technique or terrain slopes. The flight test was executed by operational pilots who were instucted to use emergency recovery procedures. This was done to achieve a spread in recovery altitudes representative of operational warning and recovery altitudes. These criteria are, therefore, statistically justifiable for judging the performance of a GCWS.

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GLOSSARY OF TERMINOLOGY

Above Ground Level (AGL) The distance from the altitude sensor on the aircraft to the ground directly beneath it.

Average Terrain Slope The angle of a straight line starting at the valley and ending at the peak of a slope. Also referred to as Terrain Angle.

Bunt Maneuvers Maneuvers with a g between -0.5 and 0.5, bank angle less than 30 degrees, and sink rate less than 144 ft/sec.

Early Warning Any warning issued to the pilot which results in a recovery which is above the MAXA and below the limit altitude.

Emergency recovery procedure Pilot reacts up to but within 1 second after the initiation of audible sound in the pilot's headset using a large percentage of the maximum control authority available to him.

Flight Test Maneuver Descending Constant attitude turn.

Good Warning Any warning issued to the pilot which results in the aircraft's recovery altitude being within the allowable recovery altitude limits.

Late Warning Any warning issued to the pilot which does not permit sufficient altitude for avoiding penetration of the minimum allowable recovery altitude when the emergency recovery procedure is executed or failure to provide a warning, causing penetration of the minimum allowable recovery altitude.

Limit altitude The highest recovery altitude at which a recovery shall occur as shown in Figure 1.

Maneuver Type I (Accelerated Dive) Any maneuver where the aircraft is at greater than 55 degrees of bank and has greater than 16 ftpsps acceleration towards the ground. Defined at the time of the leading edge of the warning signal.

Maneuver Type II (Banked Turns) Any maneuver where the aircraft is at greater than 55 degrees of bank and less than 16 ftpsps acceleration towards the ground. Defined at the time of the leading edge of the warning signal.

Maneuver type III Any maneuver in which the aircraft's angle of bank is less then 55 degrees. Defined at the time of the leading edge of the warning signal.

Maximum Altitude (MAXA) The highest desirable recovery altitude (AGL) (see Figure 1).

Minimum Altitude (MINA) The lowest desirable recovery altitude (AGL) (see Figure 1).

Minimum Design Altitude Warning (MDA) The minimum altitude above the terrain for which the system is designed to issue a warning. Can never be called a nuisance or early warning.

Nuisance Warning Any warning which the pilot states is unacceptable.

Pilot Reaction Time The time from the initiation of audible sound to the pilot's headset to the time at which the pilot makes a control input which uses at least 25% of the control force available to him.

Pop-Up-Maneuvers 3 to 4 G pull up from low altitude to acquire the target. Followed by a 135 degree bank angle change and 3 G pull to a 45 degree heading change to acquire the target. Should be performed over flat terrain and up and down ridge lines.

Recovery Altitude The first altitude (AGL) at which the ground closure rate becomes zero following a warning. Unless the pilot continues the recovery maneuver and a second minimum occurs due to terrain rise.

Slice Backs A 180-to 220-degree heading change using 120 to 150 degrees of bank and up to 5.0 g (3000 ft to 10,000 ft maximum altitude).

ZSU Breaks A 135 degree descending heading change using 90 to 120 degrees of bank and 3-5 g and unload roll-out-1 g (500 to 200 feet maximum altitude).

LIST OF ABBREVIATIONS

AGL	Above Ground Level
CFIT	Controlled Flight Into Terrain
GCWS	Ground Collision Warning System
LAWS	Low Altitude Warning System
MAXA	Maximum Altitude
MDA	Minimum Design Altitude
MINA	Minimum Altitude
TBD	To Be Determined

PILOT QUESTIONNAIRE

1. Do you feel the "pull-up" warning alarms were initiated for the most part:

1. Too early
2. Slightly early
3. Just right
4. Slightly late
5. Too late

2. Did the warning system get your attention?

1. Yes, all the time.
2. Yes, most of the time
3. Occasionally
4. Seldom
5. Never

3. How often did you get nuisance warnings?

1. All the time
2. Most of the time
3. Occasionally
4. Seldom
5. Never

4. Were there any instances, in a general sense, where the system provided no warning when it should have? Describe the circumstances.

____

____

____

____

5. What do you feel is the usefullness of a ground collision warning.

1. Essential
2. Extremely useful
3. Useful
4. Moderate usefullness
5. Useless

6. How often, if ever, would you tend to over rely on a Ground Collision Warning System (i.e., using the system as a pull-up cue during a bombing mission)?

1. All the time
2. Frequently
3. Occasionally
4. Seldom
5. Never

APPENDIX

7. How would you rate the adequacy and suitability of the Ground Collision warning?

1. Excellent, optimum warning system
2. Very good
3. Good
4. Satisfactory, but improvements could be made
5. Satisfactory, but improvements are essential
6. Poor
7. Very poor

8. Were there any design considerations ommitted that you consider essential to a Ground Collision Warning System?

9. Comment on the adequacy of this simulation for rating the Ground Collison Warning System?

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SUPPLEMENTARY

INFORMATION

ERRATA

MEMORANDUM FOR ASD/ENFTC WPAFB OH

Subject: Technical Report Errata

Attached are corrections to errata printed in ASD-TR-88-5034. Please correct your copy of this document. Thankyou.

Diane Shah

1 atch-Page 10 of report

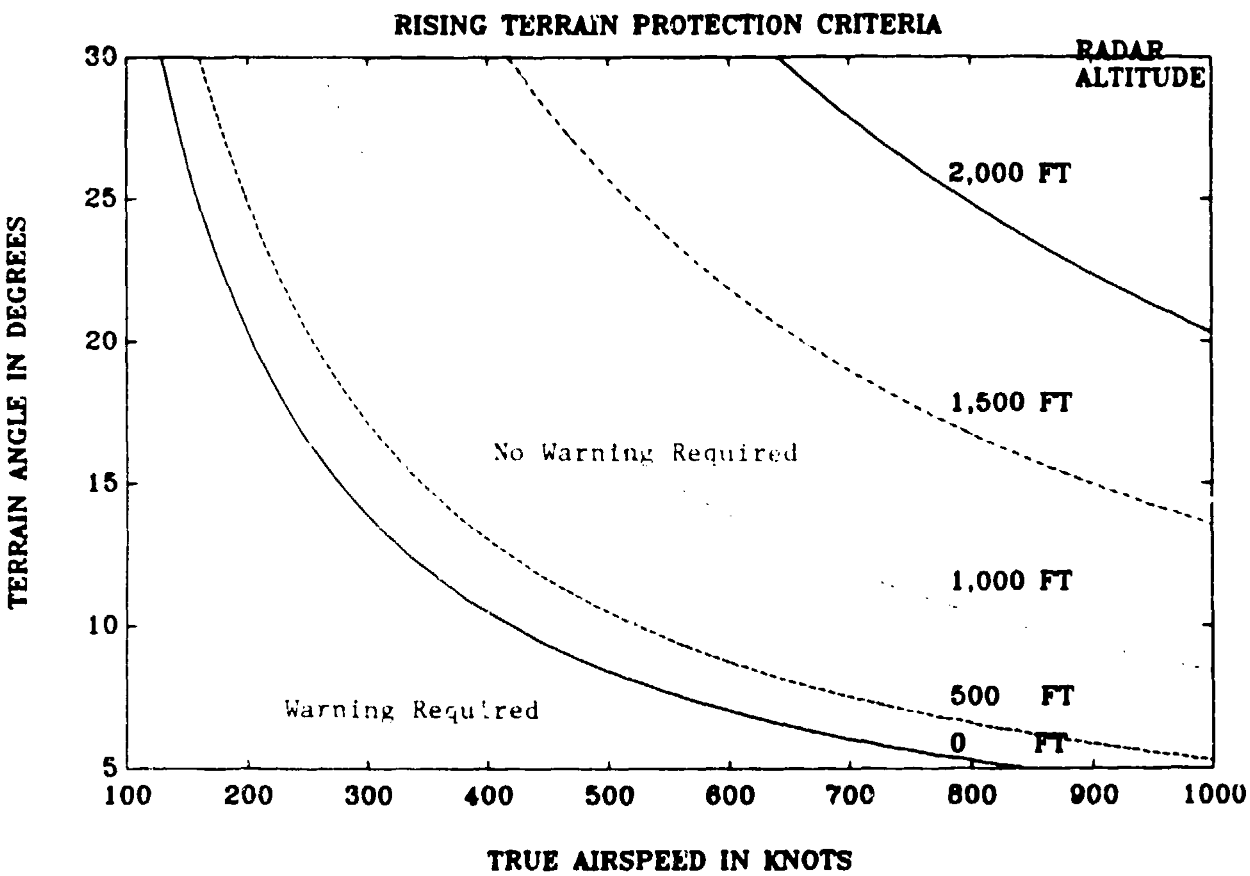
RISING TERRAIN PROTECTION CRITERIA
RADAR ALTITUDE
2,000 FT
1,500 FT
1,000 FT
500 FT
0 FT
No Warning Required
Warning Required
TERRAIN ANGLE IN DEGREES
30
25
20
15
10
5
100
200
300
400
500
600
700
800
900
1000
TRUE AIRSPEED IN KNOTS

FIGURE 2